

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<small>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Service, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.</small>					
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 1-26-2010		2. REPORT DATE Final		3. DATES COVERED (From - To) May 2008 -- December 2009	
4. TITLE AND SUBTITLE Phase-resolved reconstruction and forecasting of ocean wavefields using scanning-sensing wave measurements				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER N00014-08-1-0694	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Yue, Dick K.P. and Yuming Liu				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Massachusetts Institute of Technology 77 Mass Avenue Cambridge, MA 02139				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) ONR, Code 322PO 875 North Randolph Street, Suite 1425 Arlington, VA 22203				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER	
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution is unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT This research focuses on the understanding of feasibility and reliability of deterministic reconstruction and (short-time) forecasting of realistic ocean wavefield evolution by using phase-resolved wavefield simulations together with radar-sensed wave data. Direct comparisons between the reconstructed and forecasted wavefields and the radar-sensed realistic ocean wavefields are obtained. The validity, efficacy and limitation of the overall approach are evaluated and quantified.					
15. SUBJECT TERMS Deterministic ocean wavefield reconstruction, short-time wavefield forecasting, scanning-sensing, wave measurement, ocean wavefield evolution					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 6	19a. NAME OF RESPONSIBLE PERSON Yue, Dick K.P.
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code) 617-253-6823

Phase-Resolved Reconstruction and Forecast of Ocean Wavefields Using Scanning-Sensing Wave Measurements

Dick K.P. Yue

Center for Ocean Engineering
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

phone: (617) 253- 6823 fax: (617) 258-9389 email: yue@mit.edu

Yuming Liu

Center for Ocean Engineering
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

phone: (617) 252- 1647 fax: (617) 258-9389 email: yuming@mit.edu

Award Number: N00014-08-1-0694

<http://www.mit.edu/~vfri/>

LONG-TERM GOAL

To develop and demonstrate an advanced capability of deterministic reconstruction and (short-time) forecasting of realistic ocean wavefield evolution, using scanning wave sensing data and efficient phase-resolved nonlinear wave simulations.

OBJECTIVES

Of special interest and focus is incorporation and assimilation of radar measurements of ocean surface waves in phase-resolved simulation of nonlinear ocean wavefield evolution. To reach this objective, fundamental research and technical developments in the following four areas are required:

1. Development of a phase-resolved wave reconstruction and prediction capability incorporating with radar sensed wave data
2. Understanding of reliability/accuracy/robustness and limitations of the overall approach
3. Assessment of effects of noise, uncertainties, and interpretation errors in radar measurements upon the accuracy of wavefield prediction
4. Direct quantitative comparisons between wave model prediction and field measurements.

APPROACH

We develop and apply a comprehensive deterministic computational model for intermediate scale, $O(10)$ km, wave environment prediction by integrating whole-field and multiple-point direct

measurements of the ocean wave and atmospheric environment with nonlinear simulation-based reconstruction of the wavefield. The wave reconstruction is based on phase-resolved simulation of nonlinear surface wave dynamics, and utilizes hybrid (from different types of sensors) measurements that may contain noise, uncertainty and gaps (Wu 2004; Yue 2008). The simulations will incorporate physics-based wind forcing, wave-breaking dissipation, and current models.

WORK COMPLETED

The main objective of this research is on the understanding of feasibility and reliability of applying nonlinear wavefield simulations together with radar sensed wave data to obtain a phase-resolved reconstruction and prediction of realistic ocean wavefield evolution. We thus focus on the accuracy of wave reconstruction and forecasting that might be affected by imperfect wave data or misinterpretation of the predicted wavefield.

- Investigate the effects of uncertainty and incompleteness in scanning sensed wave data (such as shadows in radar sensed data) upon the accuracy and reliability of the wave reconstruction and prediction. Of special interest is the determination of wave predictable regions for given hybrid sensed wave data.
- Apply the high-resolution wave reconstruction and forecasting capability to evaluate the accuracy, effectiveness and robustness of the interpretation schemes in transforming radar signals to ocean wave information. In particular, we developed algorithms based on nonlinear wave reconstruction to determine the wave information in shadow zones of radar measurements and to extract current speed and direction from the radar sensed surface data.
- Perform direct comparisons between quantitative field radar measurements and phase-resolved wave reconstruction/forecasting to evaluate and quantify the validity, efficacy, and limitations of the overall approach.

RESULTS

We extend the phase-resolved wave reconstruction/prediction model to include radar sensed wave data, develop algorithms based on the nonlinear reconstruction for determining the wave information in shadows of radar measurements and for extracting current information from the radar data, and apply the wave reconstruction and forecasting capability to synthetic and realistic ocean waves. We present sample results on the extraction of current information from radar wave measurements and on the understanding of the accuracy of the reconstructed/predicted wavefield based on specified radar sensed wave data as a function of space and time.

The presence of current affects the wave characteristics. In order to obtain a proper prediction of wavefield evolution, the effect of current must be included in wave modeling. Thus, accurate determination of current speed and direction from radar sensed wave data is of significance. The developed wave reconstruction scheme can be applied to properly determine the current information from radar sensed wave data. A sample application of this capability is illustrated in figure 1 which shows the time variation of the correlation coefficient between the reconstructed/predicted wavefields and the WAMOS radar sensed wave data. The radar wave data is used in the reconstruction at $t/T=0$ only. In the reconstruction, current is treated in three different ways: (i) without current; (ii) setting

current $U=U_{\text{radar}} = 0.66\text{m/s}$ and direction $\theta = 337^\circ$ (which are estimated empirically from radar data); and (iii) treating current speed U and direction θ as unknowns that are to be determined by optimization in reconstruction. In the third treatment, we obtain $U = 0.89 \text{ m/s}$ and $\theta = 341^\circ$, which give the best prediction of the wavefield evolution by comparing to the radar data (not used in the prediction), as shown in figure 1. This example indicates that it is possible to obtain a better estimate of current information from radar sensed wave data using the wave reconstruction algorithm.

For a given radar sensed wave data in a certain domain D at a particular time (say $t = 0$), we can reconstructed the wavefield in D at $t = 0$ and then use the nonlinear wave simulation to predict the evolution of the reconstructed wavefield in D for $t > 0$. In the evolution of the wavefield, waves outside D (that are not represented in the radar sensed data) would enter slowly into D and deteriorate the predicted wave motion near the boundary of D . The region in D affected by this increases with time. Eventually the whole domain of D is influenced and the reliability of the predicted wave motion is completely lost. In other words, for a given radar sensed wave data in D at time $t=0$, there exists a predictable region Q inside which the wavefield evolution can be reliably predicted based on the reconstructed wavefield in D at $t = 0$. In general, Q coincides with D at $t = 0$, and then becomes smaller and moves in the wave direction as the evolution time increases. Q is dependent on the properties of the wavefield, wave propagation direction, and size of D .

To illustrate this, we use a synthetic radar data in a domain D of $1\text{km} \times 1\text{km}$ at a particular time (say $t=0$), as shown in figure 2a, to obtain a reconstruction of the wavefield at $t = 0$ and then to predict the subsequent evolution of the wavefield. The radar wave data is chosen from a larger synthetic wavefield of $30 \text{ km} \times \text{km}$, whose evolution is computed using a direct phase-resolved wave simulation tool, SNOW. This synthetic wavefield is initially given by a JOHNSWAP spectrum with significant wave height $H_s = 12 \text{ m}$, peak period $T = 13\text{s}$, enhance parameter $\gamma = 5$, and spreading angle $\Theta = 80^\circ$. The major propagation direction is along the positive x direction. To understand the reliability/accuracy of the predicted wavefield evolution with time, we compare the time history of wave elevations in the predicted wavefield with the original synthetic wavefield at three locations A, B, C, as shown in figure 2a. The comparisons are shown in figure 2b. It is seen that the predicted wave elevations at A and C start deviating largely from that of the original wavefield at $t/T \sim 2$ as A and C are respectively closer to the upstream and side boundaries of D . Good comparison for the elevation at B extends to $t/T \sim 5$ as B is located near the downstream boundary of D . This confirms the existence of a predictable region Q for a specified radar wave measurement in D at $t=0$, which becomes smaller as the wavefield evolution continues.

IMPACT/APPLICATIONS

Advances in large-scale nonlinear wave simulations and ocean wave sensing have recently made it possible to obtain phase-resolved high-resolution reconstruction and forecast of nonlinear ocean wavefields based on direct sensing of the waves. Such a capability will significantly improve ocean-surface sensing measurements and deployment, and data assimilation and interpretation, by providing a comprehensive wave-resolved computational framework. Another important potential application of this is to greatly increase the operational envelopes and survivability of naval ships by integration of such capability with ship-motion prediction and control tools.

RELATED PROJECTS

The present project is related to the project entitled “High-Resolution Measurement-Based Phase-Resolved Prediction of Ocean Wavefields” (N00014-08-1-0610). The present project focuses on the understanding of fundamental algorithms and accuracies/reliabilities of the developed deterministic wavefield reconstruction and prediction capability while the related project focuses on the application of the wave reconstruction/prediction capability to realistic ocean environment.

REFERENCES

1. Wu, G. 2004 Direct simulation and deterministic prediction of large-scale nonlinear ocean wave-field. Ph.D Thesis, Massachusetts Institute of Technology, Cambridge, MA.

PUBLICATIONS

1. Xiao, W., Henry, L., Liu, Y., Hendrickson, K. & Yue, D.K.P. 2008 Ocean Wave Prediction Using Large-Scale Phase-Resolved Computations. *Proceedings of the DoD HPCMP Users Group Conference*, June, 2008, Seattle, WA. [published]
2. Yue, D.K.P. 2008 Nonlinear Wave Environments for Ship Motion Analysis, *27th Symposium on Naval Hydrodynamics*, October 5 – October 10, 2008, Seoul, Korea [published]
3. Liu, Y. & Yue, D.K.P. 2009 Large-Scale Phase-Resolved Simulations of Ocean Surface Waves. *OSB Oceanography in 2025 Workshop*, January, 2009, San Diego. [published]
4. Xiao, W., Liu, Y. and Yue, D.K.P. 2009 Ocean Wave Prediction Using Large-Scale Phase-Resolved Computations, *Proceedings of the DoD HPCMP Users Group Conference* 2009, June, San Diego, CA [published]

STUDENT GRADUATED

One male and one female MSs.

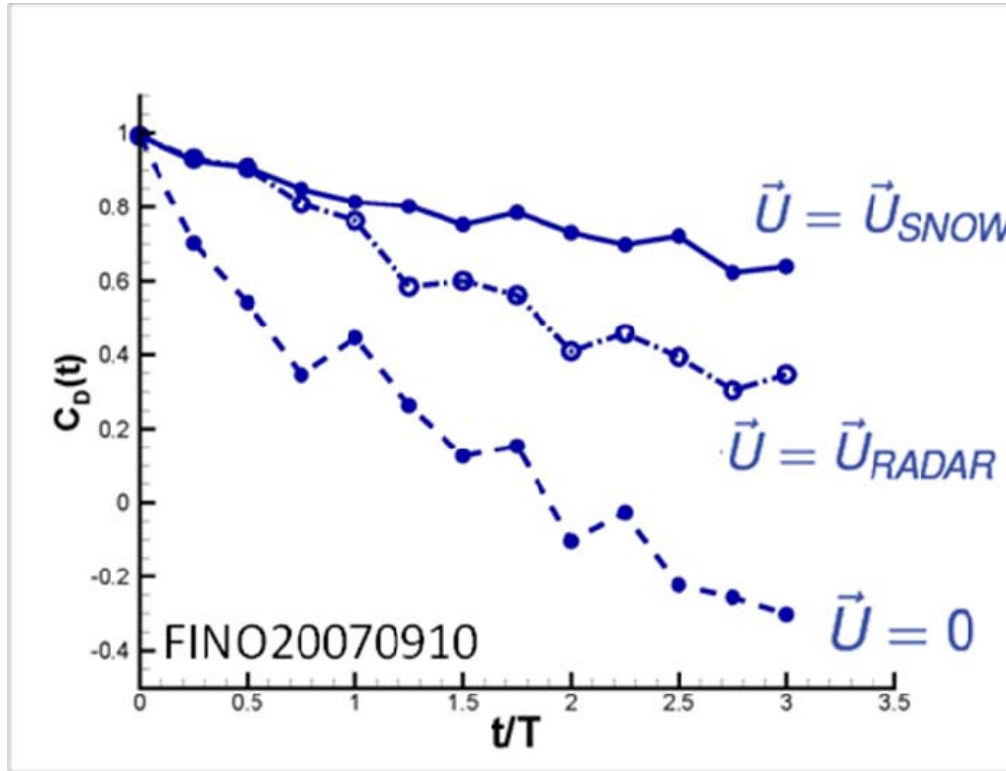
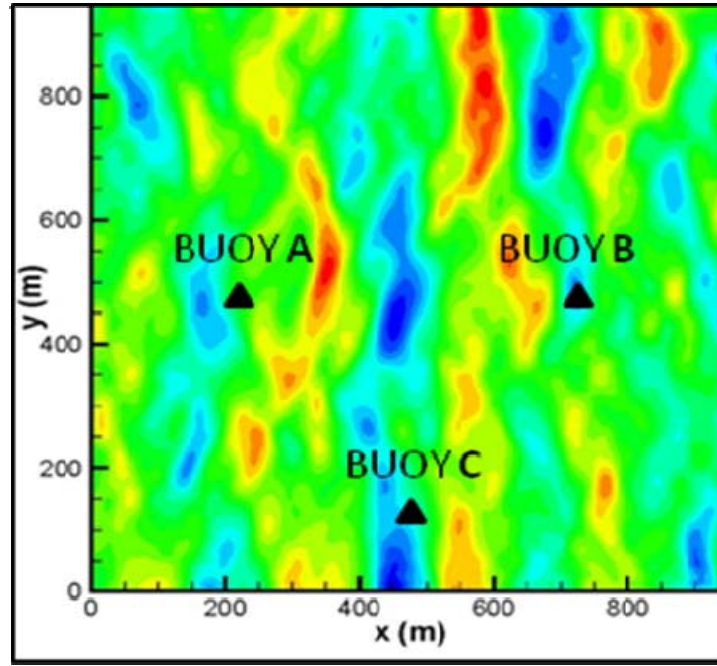
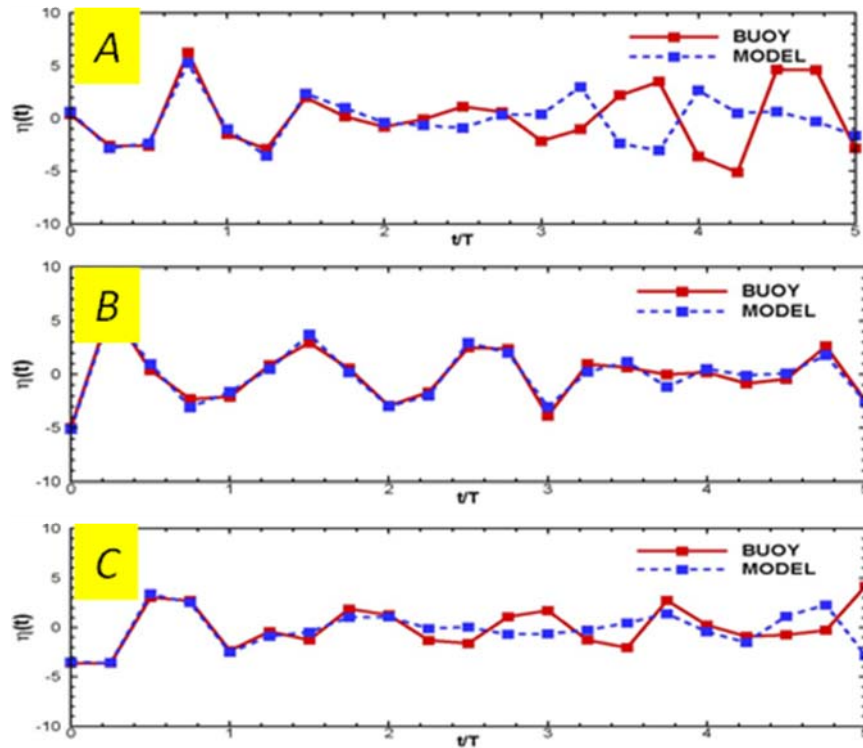


Figure 1: Correlation coefficients between the reconstructed/predicted wavefields and the original radar sensed wave data as a function of time. Wave reconstructions are obtained based on the radar sensed wave data at $t/T=0$ with current speed $U=0$, $U=U_{\text{radar}}=0.66\text{m/s}$ (estimated empirically from radar data), and $U_{\text{snow}}=0.89\text{ m/s}$ (determined by optimization in wave reconstruction).



(a)



(b)

Figure 2. (a) A surface wave image in a $1\text{km} \times 1\text{km}$ domain, chosen from a large synthetic wavefield of $30\text{km} \times 30\text{km}$, used as radar sensed wave data for wave reconstruction. (b) Comparison of time histories of wave elevations in the reconstructed/predicted and original wavefields at locations A, B, and C: results from the original wavefield (read line) and from the predicted wavefield (blue line).